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The Adipic Acid Enhanced Flue Gas Desulfurization Process for Industrial Boilers. Volume 2. Technical Assessment

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The Adipic Acid Enhanced Flue Gas Desulfurization Process for Industrial Boilers; Vol. 2. Technical Assessment

Project Report

by

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ABSTRACT

The Industrial Environmental Research Laboratory of the Environmental Protection Agency has sponsored an evaluation of an adipic acid-enhanced limestone flue gas desulfurization system on industrial boilers at the Rickenbacker Air National Guard Base. The SO_2 removal efficiency with the adipic acid averaged 94.3 percent over a 30 day period. In a prior test using only limestone, the system averaged 65.8 percent removal. Economic calculations for an industrial boiler adipic acid-enhanced limestone FGD system indicate a slight reduction in both capital and operating expenses relative to a limestone only system designed for 90 percent SO_2 control of 3.5 percent sulfur coal. The costs are competitive with the dual alkali system. The successful demonstration of the adipic acid-enhanced limestone system increases the number of demonstrated technologies available to a potential user.

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SECTION 1

SUMMARY

Based upon the results obtained in the Rickenbacker Air National Guard Base (RANGB) FGD system testing with adipic acid and the economic calculations performed in this report, it appears that an adipic acid-enhanced limestone FGD process compares favorably both technically and economically with other commercially available and demonstrated industrial boiler FGD processes. The results obtained by TVA on the similar-sized Shawnee system and the utility scale demonstration at City Utilities of Springfield confirm that adipic acid-enhanced limestone systems are capable of achieving 90 percent or greater SO_2 removal efficiencies. The bases for these conclusions are summarized below and reflect both the results of the testing at RANGB and the economic, energy, and environmental considerations of adipic acid systems applied to new industrial boilers.

1.1 RANGB RESULTS

PEDCo Environmental Inc. performed the testing at RANGB including the SO_2 monitor certification and process chemistry analysis.[1] An important result of the testing is that, for a 30-day period with an adipic acid concentration of about 2000 ppm, the SO_2 removal averaged 94.3 percent. In previous tests of the same duration, the system averaged 65.8 percent removal when using only limestone and 91.5 percent when using lime. Similar increases in SO_2 removal efficiency at Shawnee and Springfield have also been observed for adipic acid-enhanced operation over base line limestone-only performance.

1.2 INDUSTRIAL BOILER ADIPIC ACID-ENHANCED FGD PROCESS COMPARISON

The RANGB limestone FGD system has a "one-of-a-kind" design that is not likely to be used in future installations. Therefore, the development of material and energy balances and cost estimates for this type of design was not undertaken. As discussed previously, the RANGB results support the results obtained with the Shawnee FGD system using a turbulent contact absorber (TCA). Although it treats utility flue gas, the Shawnee FGD test facility is approximately the same size as that required for a medium size industrial boiler. In this report the Shawnee data (with and without adipic acid addition) provide the bases for an economic, energy, and environmental impact analysis of industrial boiler FGD systems.

A technology assessment report on flue gas desulfurization for industrial boiler applications[2] evaluated five different FGD systems for five sizes of model industrial boilers burning a variety of fuels and with varying SO_2 removal efficiencies. This report examines the differences between the adipic acid-enhanced system and the base limestone system for both 105 and 400 x 10^6 Btu per hour boilers burning 3.5 percent sulfur Eastern coal requiring 90 percent SO_2 removal. The system cost results are compared to those for an equivalent dual alkali system. It is expected that the economic, energy, and environmental impact trends exhibited for these cases will hold true for boiler systems with different capacities.

Table 1-1 presents the capital investment and annual costs for the adipic acid system, the limestone base case, and a dual alkali system for the model boilers. The adipic acid-enhanced limestone system is 5-6 percent lower in capital investment and 2-3 percent lower in operating cost than the limestone base case. Although there is considerable uncertainty in the overall cost of the limestone systems (estimated to be ±30 percent), the relatively small cost advantage for the adipic acid system is real because the costs were estimated for various sub-systems based on technical factors and material balances. Some of the technical issues, such as differences in dewatering efficiency between sludges from adipic acid-enhanced and unenhanced systems, may be somewhat

site specific. However, the difference between costs of enhanced and unenhanced sub-systems based on the technical factors do reflect actual size differences even though the absolute cost of each sub-system is known only within ±30 percent. Table 1-1 also shows that both adipic acid-enhanced (2000 ppm) and unenhanced limestone systems have approximately equal capital and operating costs compared to the dual alkali system.

TABLE 1-1. CAPITAL INVESTMENT AND ANNUAL* COSTS FOR INDUSTRIAL BOILER FGD SYSTEMS (1978 DOLLARS)

Size (10^6Btu/hr)	FGD System	Capital Cost ($1,000)	Annual Cost* ($1,000)
150	Limestone (without Adipic Acid)	1,568	785
150	Limestone (with Adipic Acid)	1,488	765
150	Dual Alkali**	1,657	778
400	Limestone (without Adipic Acid)	2,714	1,435
400	Limestone (with Adipic Acid	2,586	1,412
400	Dual Alkali**	2,576	1,328

*Annual cost include annual O&M plus capital related costs.
**Ref 3 gives cost breakdown for dual alkali system.

The annual cost advantage for the adipic acid system over the limestone base case reflects the lower capital costs and lower energy consumption. The energy consumption of the adipic acid process is approximately 50 percent of that used in the base case limestone system. The adipic acid systems require less than one percent of the boiler input energy while the limestone-only systems require 1.5-1.8 percent. Stack gas reheating is not used in any application. This large reduction is because of the increased SO_2 removal capability of the adipic acid-enhanced limestone slurry and the resulting size reduction of the slurry circulation pumps and lower gas phase pressure drop across the TCA scrubber required to achieve the desired removal. The actual design parameters for each system were obtained from correlations of the Shawnee data.

SECTION 2

INTRODUCTION

The Industrial Environmental Research Laboratory (IERL) of the Environmental Protection Agency (EPA), is currently developing the adipic acid-enhanced limestone flue gas desulfurization process and gathering background information to support a New Source Performance Standard for industrial boilers. In order to demonstrate the control technology for these sources, IERL sponsored an evaluation of an existing industrial boiler limestone flue gas desulfurization (FGD) system, using adipic acid to enhance SO_2 removal. The test site was the Rickenbacker Air National Guard Base (RANGB) outside of Columbus, Ohio. The site consists of 6 industrial boilers which supply hot water during the heating season for the base facilities. A Research-Cottrell/Bacho lime/limestone FGD system is used to control both particulate and SO_2 emissions from these stoker-fired boilers. Maximum heat generation capacity is 210 million Btu's per hour.

The host site was chosen for two reasons:

- RANGB is the only coal-fired industrial boiler which uses a limestone FGD system,
- The RANGB FGD unit has been tested previously using both lime and limestone sorbents. Tests with lime sorbent resulted in average SO_2 removal efficiencies of about 90% while limestone yielded less than 70%. Therefore the potential exists for a significant improvement in SO_2 removal efficiency when using limestone.[4]

The increasing differential cost between clean fuels (oil, gas) and coal provides the driving force for continued increases in coal-fired industrial boiler capacity. Due to the lower cost of limestone compared to other alkali

reagents, there is an economic incentive to demonstrate reliable and efficient operation of a limestone based industrial-sized FGD system. The addition of an alternative FGD technology to the list of demonstrated technologies will give a potential user greater flexibility in the selection of control equipment. Typically, limestone systems do not easily maintain SO_2 removal efficiencies as high as those for sodium-based systems which are the predominate FGD system used for industrial boiler applications. Based on testing at the EPA/TVA Shawnee prototype facility, the addition of a relatively small amount of adipic acid can increase the removal capability of limestone systems to levels obtained by sodium systems. Economic studies based on the prototype results indicate that adipic-acid enhanced systems may have a cost advantage over unenhanced limestone systems for utility applications.[5]

In order to demonstrate this technology, EPA has funded a study to determine the effectiveness of adipic acid in enhancing the performance of the RANGB FGD system. EPA has also funded testing of a utility system, the 194 Mw unit of City Utilities, Springfield, Missouri. Testing was completed on the Springfield system in the fall of 1981.

PEDCo Environmental Inc. was contracted by EPA to collect continuous SO_2 removal efficiency data from the RANGB unit and to characterize the process parameters of the adipic acid-enhanced system. The results of their study are published separately and summarized in this report. Radian Corporation was contracted by EPA to monitor the operation at RANGB. Additionally, Radian evaluated the results at RANGB and determined their applicability to new industrial boiler FGD systems. The approach used for this study was similar to that used in the FGD Technology Assessment Report for Industrial Boilers.[6] Two model boilers (150 and 400 x 10^6 Btu/hr) using limestone FGD systems without adipic acid addition were used as the base cases. The base case systems were then compared to adipic acid-enhanced systems on economic, energy, and environmental impact bases. Section 3 discusses the performance of adipic acid in an FGD system. Sections 4, 5 and 6 present the energy, economic, and environmental comparison of the adipic acid-enhanced systems with the base case limestone systems.

SECTION 3

PERFORMANCE OF ADIPIC ACID-ENHANCED LIMESTONE SLURRY

The addition of adipic acid to limestone-based scrubbing liquors has been shown to increase both the SO_2 removal efficiency and the limestone utilization. Work has been performed on bench, pilot, and commercial scale systems to demonstrate these observations. This section discusses the efficiency improvement obtained by using adipic acid at the RANGB facility. A discussion of adipic acid chemistry is presented first, followed by a process description and a summary of the results of the test program.

3.1 ADIPIC ACID CHEMISTRY

Although calcium-based systems are generally attractive from an economic standpoint, reagent and calcium-sulfur species solubility constraints pose design and operating limitations on calcium systems compared to sodium-based systems. Calcium systems generally require high liquid-to-gas ratios (L/G's) to achieve SO_2 removal and larger reaction tanks to dissolve the alkaline reagent and to precipitate the calcium sulfite and calcium sulfate formed. The relatively low solubility of calcium-sulfur salts also creates the possibility of chemical scaling which in turn makes more open configuration scrubber designs attractive in calcium systems. Adipic acid enhances SO_2 removal (allows lower L/G for equivalent removal compared to unenhanced system), improves limestone utilization and aids in reliable limestone system performance. Thus, an adipic acid-enhanced limestone system should provide an attractive alternative to sodium-based systems.

3.1.1 SO_2 Removal

During the SO_2 removal step in the absorber, the SO_2 is physically absorbed and then reacts according to the following reaction mechanism:

$$SO_2(g) \overset{H_2O}{\rightleftarrows} SO_2\ (aq) + H_2O \rightleftarrows H^+ + HSO_3^-$$

Soluble alkaline species such as $SO_3^=$, $CO_3^=$, and HCO_3^- react to neutralize the acid formed and maintain a driving force for SO_2 absorption:

$$H^+ + SO_3^= \rightleftarrows HSO_3^-$$

However, in limestone systems the concentrations of these alkaline species are constrained by solubility, and the alkalinity required must be provided by maintaining higher L/G's and higher levels of solid phase alkalinity. (The solids dissolution is relatively slow and limits the SO_2 sorption rate). The alkaline species are much more soluble in sodium systems so the L/G's can be much lower.

Adipic acid is a dicarboxylic acid which acts as a buffer in the pH range encountered in most limestone scrubbers. Adipic's two pKa's are 5.4 and 4.4 (weaker acid than H_2SO_3) so addition of adipic acid to the scrubbing liquor promotes SO_2 removal.

$$2SO_2(aq) + 2H_2O \rightleftarrows 2H^+ + 2HSO_3^-$$
$$2H^+ + Ad^= \rightleftarrows H_2Ad$$

The adipic ion reacts with the hydrogen ion to buffer the pH and maintain a driving force for SO_2 removal. Addition of 2000 ppm adipic acid can more than double the normal dissolved alkalinity concentration in a limestone system.

In addition to improving SO_2 mass transfer, use of adipic acid will lower the amount of limestone which dissolves in the scrubber and should lessen the chances of chemical scaling. Thus, adipic acid addition should improve equipment reliability as well.

3.1.2 Limestone Dissolution

Adipic acid also acts as a buffer in the limestone dissolution step (stronger acid than H_2CO_3):

$$CaCO_3(s) + H_2O \rightleftarrows Ca^{++} + CO_3^{=}$$
$$H^+ + CO_3^{=} \rightleftarrows HCO_3^-$$
$$H^+ + HCO_3^- \rightleftarrows H_2O + CO_2(g)$$
$$H_2Ad + CO_3^{=} \rightleftarrows Ad^{=} + 2H_2O + CO_2(g)$$

The associated adipic species reacts with the dissolved $CO_3^{=}$ ion to maintain a driving force for limestone dissolution. The adipate ion thus formed is ready to act again as a buffer in the SO_2 removal step.

In addition, since the adipic acid promotes the SO_2 removal reaction by providing additional liquid phase alkalinity, less solid phase calcium carbonate is required in the slurry for SO_2 removal. In fact, addition of sufficient adipic acid provides the buffer capacity required for SO_2 absorption at scrubber feed pH's of 5.0 or slightly lower. This low pH operation further enhances the driving force for limestone dissolution in the reaction tank and increases the limestone utilization.

In summary, the use of adipic acid promotes the sorption of SO_2 by buffering the scrubber slurry and promotes the dissolution of limestone by buffering the reaction tank liquor and by making it possible to operate at lower pH set points. Increased SO_2 removal efficiency and limestone utilization are therefore possible with less risk of chemically scaling the absorber. In addition, operation with high levels of dissolved chloride or at high sulfite oxidation levels should not impair the efficiency of adipic acid as happens with many inorganic additives.

3.2 PROCESS DESCRIPTION AT RANGB

3.2.1 Boiler Arrangement

The FGD system at Rickenbacker scrubs the flue gas from six stoker-fed coal-fired boilers. Five of the boilers are rated at a nominal 30 million Btu per hour and the newest boiler is rated at 60 million Btu per hour. The recirculating hot water is typically sent to the base facilities at 400°F and returned to the boilers at 300°F. Coal is spread on the under air flow grates to a depth of 3-5 inches. The grates are mechanically rotated in order to feed ash to the pneumatic disposal system. Combustion air, supplied by forced draft fans, produces excess oxygen levels from 14 to 18 percent.

During the test program, the oldest boiler (#3) was not brought on line. Generally 2-3 boilers were required to supply hot water for the base heating requirements, while the other units were kept on standby. Total coal consumption was 3980 tons in 44 days which produced an average heat input of 101 million Btu per hour. Most of the test period occurred during unseasonably warm winter weather, lowering the heat requirement from historical levels. The average sulfur content of the coal was 2.6 percent. The average SO_2 emission rate to the FGD system was 4.94 pounds of SO_2 per million Btu.

3.2.2 FGD System

The flue gas from the boilers was scrubbed by a Research-Cottrell/Bahco system designed for both particulate and SO_2 control. This unit was installed at the base in 1974 and has been previously tested with both lime and limestone as the alkaline reagent.[7,8,9] AB Bahco in Sweden developed this system. The unit at RANGB was the first application to coal-fired boilers; several systems have been used on foreign oil-fired industrial boilers.

Figure 3-1 is a diagram of the FGD system at RANGB. Flue gases from the six boilers are collected in a common manifold by an induced draft fan. Normal operating procedure involves maintaining a constant gas flow to the scrubber. This is accomplished by using a bypass stack to infiltrate dilution air when the boiler output falls below about 50,000 scfm. Gas flow is maintained by adjusting inlet louver dampers. A mechanical collector upstream of the fan removes large particulates from the gas. Because the gas flow is essentially constant regardless of the boiler load, changes in boiler load can significantly affect the inlet SO_2 concentration. The inlet value averaged about 700 ppm; however, values of 400 to 1000 ppm were often observed depending upon the number of boilers in operation.

Upon leaving the booster fan, the flue gas passes into the first stage of the scrubber. The gas is forced downward where it contacts mill pump liquid. The gas reverses direction, flowing upwards. Entrained liquid falls out and is caught in the first stage carryover tray. The gas continues upward, impinging on the bottom of the second stage liquor reservoir. The gas travels upward around the second stage liquor reservoir and then reverses direction and is contacted with second stage liquor. Following another carryover tray, the gas passes through a cyclonic mist eliminator before being discharged. No flue gas reheat is used.

The liquid flow through the system is fairly complex. Starting in the limestone feed tank, where the reagent is added, the slurry is pumped to the second stage level reservoir. Some of this liquid is entrained in the gas and subsequently is caught in the second stage carryover tray. The desired liquor level on the second stage is maintained by an external level tank. Originally, the weirs in the external tanks were adjustable, permitting the pressure drop across the scrubber to be varied. The weirs could not be adjusted during this test due to rust and corrosion. Liquor from both the second stage carryover and level tray is gravity fed to the first stage. This first stage liquor is continually recirculated by the mill pump. Excess liquid from the first stage and the first stage carryover tray is gravity fed back to the limestone feed tank, completing the circuit. A bleed stream from the first stage carryover tray is used as thickener feed.

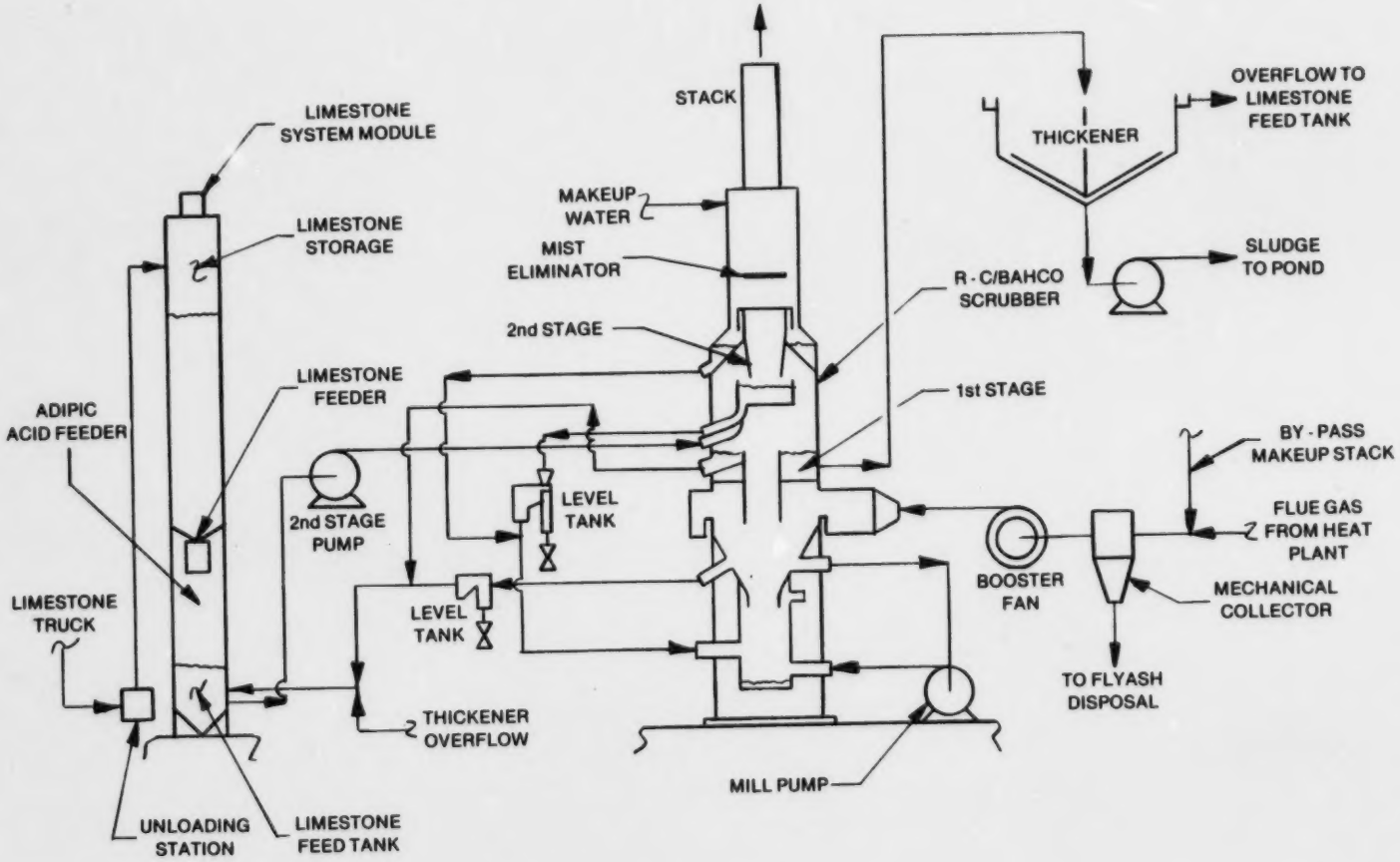


FIGURE 3-1 R-C/BAHCO FGD SYSTEM AT RANGB

Thickener overflow liquid is returned to the limestone feed tank. The thickener underflow is intermittently pumped to the sludge pond. A density meter on the mill pump line controls the disposition of the thickener underflow. When the thickener underflow is not being sent to the sludge pond, it is fed into the scrubbing loop. When the density reaches the high setpoint, the solids are sent to the pond. At the low set point, the system goes back on recycle. Usually, the system purged solids approximately 25 percent of the time. Cycling time was about two hours.

Makeup water was added at several points: (1) pump seal water; (2) water for lime slaking or limestone slurrying; and (3) flush water for scrubber internals including mist eliminator wash (mist eliminator is washed while thickener underflow is being pumped to the pond). No water is returned from the pond to the system which means the process is open loop from a water balance standpoint.

Adipic acid was added to the slaker above the limestone tank in powder form. A vibratory screw feeder was used to feed the acid. Occasionally, additional acid was added directly to the thickener in order to increase the concentration quickly.

3.2.3 Differences Between the R-C/Bahco System and a Conventional FGD Unit

The FGD system at RANGB is atypical of both other industrial boiler FGD units and commercial lime/limestone units used by utilities. Of the 123 operating industrial boiler FGD units at the end of 1979, only 2 used lime or limestone as the reagent.[10] The large majority of systems used either sodium hydroxide or sodium carbonate as the reagent.

Commercial utility lime and limestone FGD systems also differ from the RANGB unit. Although early systems often used marble beds, trays, rods, and other constrictions to promote gas-liquid mixing, many new designs are of a more open configuration to avoid scaling and plugging problems. The most popular design is a spray tower which has very few internal obstructions.

These towers allow for easier maintenance with regard to scaling and plugging. The complicated internal liquid and gas flows of the R-C/Bahco system would prove difficult to clean if severely scaled.

Besides the internal configuration, there are several other major differences between this system and typical limestone systems. Most systems have a reaction tank which has a solid phase residence time of about 10 hours. This is to allow for limestone dissolution and calcium sulfite and calcium sulfate crystal growth. At RANGB, the solids residence time in the scrubbing loop is closer to one hour. In most limestone FGD systems, low solids residence time generally causes the formation of very small crystals (resulting in poor solid-liquid separation) and poor limestone utilization, but these problems were not observed at RANGB. The periodic recycle of thickener underflow slurry may have minimized these problems.

The pressure drop across the system at RANGB was about 30 inches of water, which is very high for an FGD system. However, the system was also designed for particulate removal, which requires the higher energy to effectively remove the fly ash particles. Spray towers generally have a pressure drop of 1-2 inches of water but are not effective for particulate control.

Another characteristic of RANGB which differentiates it from most other FGD systems is the open-loop mode of operation. Excess liquid in the sludge pond is not returned to the system. Since the heating plant is only run during the winter, evaporation presumably removes most of the excess pond water in the summer. In a continuously operating system, this procedure would result in liquid discharges. Recycling the pond water back to the system would likely be used in new units in order to operate in a zero discharge mode. Recycling pond water would also reduce the adipic acid feed requirements by a factor of 2-3.

3.3 RESULTS OF ADIPIC ACID TESTING

As previously mentioned, the RANGB FGD system has been tested several times, using both lime and limestone as the alkali additive. The SO_2 removal data from this test and the previous tests are summarized in Table 3-1. The adipic acid tests show a significant improvement in SO_2 removal compared to the limestone test (without adipic acid). The reliability* of the RANGB limestone FGD system was above 90 percent during tests both with and without adipic acid. During adipic acid testing, the reliability factor was 94.7 percent. The system was only down twice, once due to an electrical outage and the second time when foreign debris plugged the thickener underflow line. During the limestone (without adipic acid) test, the reliability was 91.4 percent, with several boiler and scrubber outages related mainly to severe weather problems.

TABLE 3-1. COMPARISON OF TEST RESULTS - SO_2 REMOVAL AT RANGB

	Limestone[1]	Lime[2]	Limestone-Adipic Acid[3]
Days of Testing	42	29	30
Max % Removal	87.3	96.0	97.4
Min % Removal	51.0	86.6	90.0
Avg % Removal	65.8	91.5	94.3
Avg Boiler Load (10^6Btu/hr)	-	109	101

[1]Ref 11
[2]Ref 12
[3]Ref 13

Limestone and adipic acid consumption during the program averaged 634 and 9.5 pounds per hour, respectively. For an average adipic acid concentration of 2000 ppm, the amount of acid leaving the system in the thickener underflow averaged 9 pounds per hour. If the water from the sludge pond were

*Reliability = hours the scrubber operated divided by the hours the scrubber was called on to operate.

recycled (closed loop), the adipic consumption would probably be 50-60 percent less. Analyses performed by PEDCo indicate that limestone utilization was 70 to 96 percent.[14] No figure is available for the limestone test without adipic acid.

SECTION 4

ENERGY IMPACT OF ADIPIC ACID-ENHANCED LIMESTONE SYSTEM

This section presents the energy requirements of the limestone FGD systems (with and without adipic acid). The energy requirements of the adipic acid system are about 50 percent less than those presented in the technology assessment report[15] for the limestone FGD system without adipic acid (base case). Of the four major energy consumption areas in limestone FGD systems, two are significantly reduced when using adipic acid. These are the fan power requirements due to a lower gas side pressure drop and the SO_2 scrubbing system power requirement due to a lower L/G ratio. The raw materials handling and utilities and services electrical requirements do not change significantly. In order to calculate the energy requirements of the adipic acid-enhanced process, the required operating conditions were predicted from the Shawnee prototype and Springfield demonstration results. These conditions are discussed in Section 4.1 and are followed by a comparison of the base case and adipic acid-enhanced FGD system energy requirements.

4.1 DESIGN BASIS FOR ADIPIC ACID-ENHANCED SYSTEM

The design of the industrial boiler FGD system tested at Rickenbacker Air National Guard Base is not typical of most utility lime/limestone FGD systems. The complex liquid and gas flow passages for the RANGB system are not currently being utilized in new system designs. New systems employ scrubbers with simple internals like spray towers and Turbulent Contact Absorbers (TCA). TVA's 10 MW limestone facility at the Shawnee plant has a TCA and has been tested thoroughly with adipic acid.[16,17,18]

In the technology assessment report,[19] costs for the model boiler limestone FGD system were based on a TCA system operating in a natural oxidation mode producing sludge with a high calcium sulfite content. For comparative purposes, the adipic acid-enhanced system considered here is also a natural oxidation system. Results from the Shawnee testing and TVA economic studies indicate that an adipic acid-enhanced system may offer an additional economic advantage if designed to operate in the forced oxidation mode. This is primarily due to the reduced filter cake liquor loss rate from the system (gypsum dewaters more efficiently) and subsequent lower adipic acid loss. This advantage is somewhat offset by a higher chemical degradation rate under forced oxidation conditions, but overall the advantage seems to lie with the forced oxidation system. The natural oxidation system was selected for cost comparison purposes to provide a more straightforward comparison with the economics presented in the technology assessment report for the limestone-only system.

The specifications for the limestone base case are shown in Table 4-1. The base case conditions were obtained from results of testing at Shawnee and other systems and were presented in Section 2 of the technology assessment report. Operating parameters, L/G and pressure drop are fairly severe and are also at the upper end of the data base with regard to SO_2 removal. This is because very few limestone systems have achieved 90 percent SO_2 removal on high sulfur coal applications without some type of additive (MgO for instance).

Table 4-1 also presents the conditions estimated for 90 percent SO_2 removal using adipic acid. These conditions are based on analysis of Shawnee TCA data which was designed to simulate the full-scale utility demonstration.[20] These are not necessarily the optimum conditions for a TCA since the maximum L/G is about 50 gal/10^3 acf at full gas flow conditions. However, these conditions will achieve 90 percent SO_2 removal based on Shawnee and full-scale utility results to date.

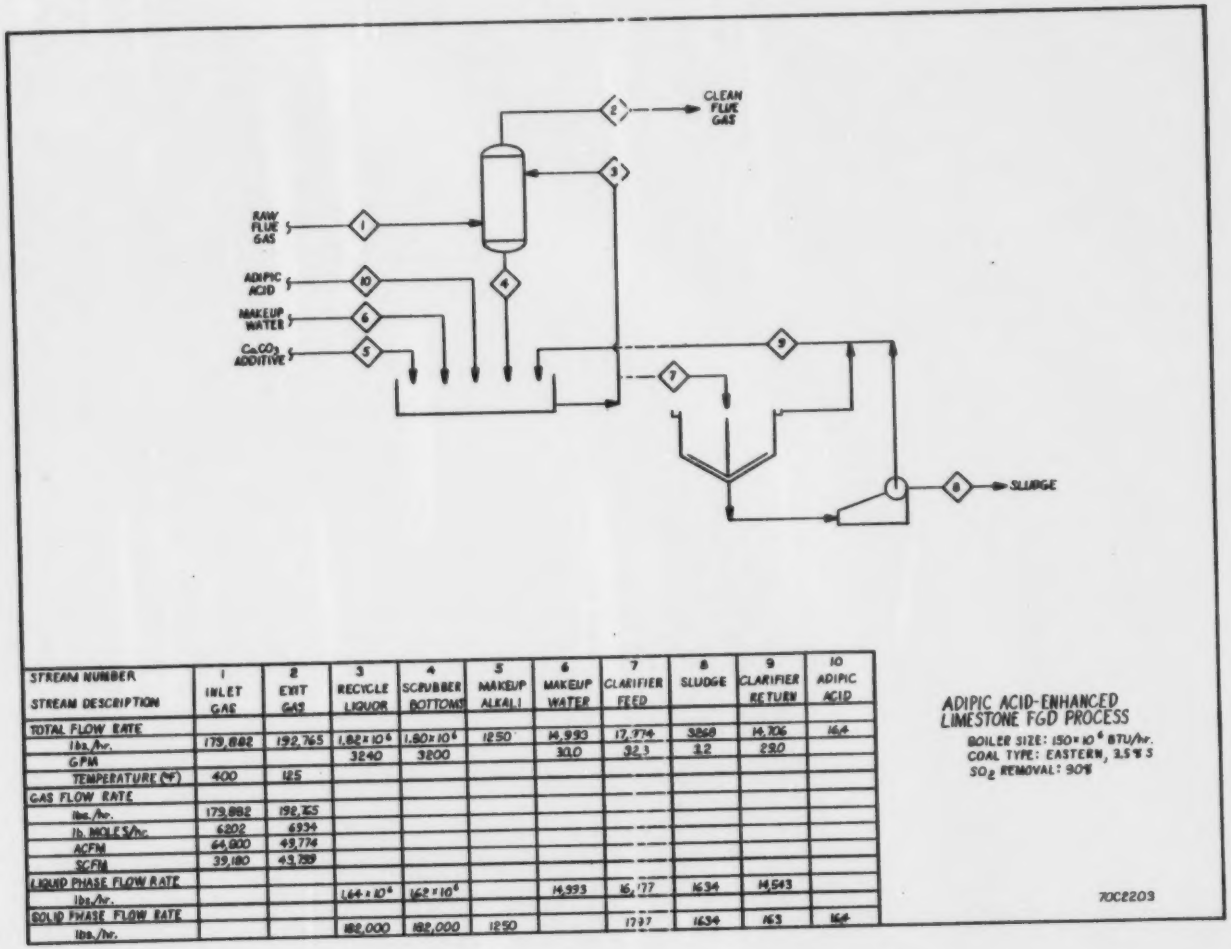
TABLE 4-1. LIMESTONE OPERATING CONDITIONS (WITH AND WITHOUT ADIPIC ACID)

Parameter	Base Case System	Adipic Acid System
L/G (gal/10^3acf)	80	50
Stoichiometry (mole $CaCO_3$/ mole SO_2 removed)	1.2	1.05
Gas Pressure Drop (inches H_2O)	17	8
Pump Discharge Pressure (psig)	15	15
Pumping Height (feet)	20	20
Bed Height (inches)	17	15
Gas Velocity (ft/sec)	13	13
Adipic Acid Concentration (ppm)	0	2000

Note that the L/G and gas-side pressure drop are lower for the adipic acid-enhanced system. Also, the limestone stoichiometry is lower, 1.05 compared to 1.2, which results in lower limestone consumption and a reduced sludge production rate.

4.2 CALCULATION OF ENERGY REQUIREMENTS

Based upon the set of design conditions selected, material balances were made for the adipic acid-enhanced systems. The results are presented in Figures 4-1 and 4-2. The base case limestone material balances are given in Figures 4-3 and 4-4. Example calculations presented throughout this section are for the 150 x 10^6 Btu/hour boiler system. The effect of adipic acid on the mass balances can be seen by examining the corresponding pairs of figures. For example, in Figures 4-1 and 4-3, the recycle liquor flow rates are 3240 and 5211 gpm respectively. This difference is because of the lower L/G in the adipic system. Likewise, the limestone requirement is 178 pounds per hour less in the adipic system for the 150 x 10^6 Btu/hr boiler. The adipic acid makeup rate was calculated at 5 times greater than the theoretical amount leaving the system in the sludge. This makeup rate has been seen at Shawnee

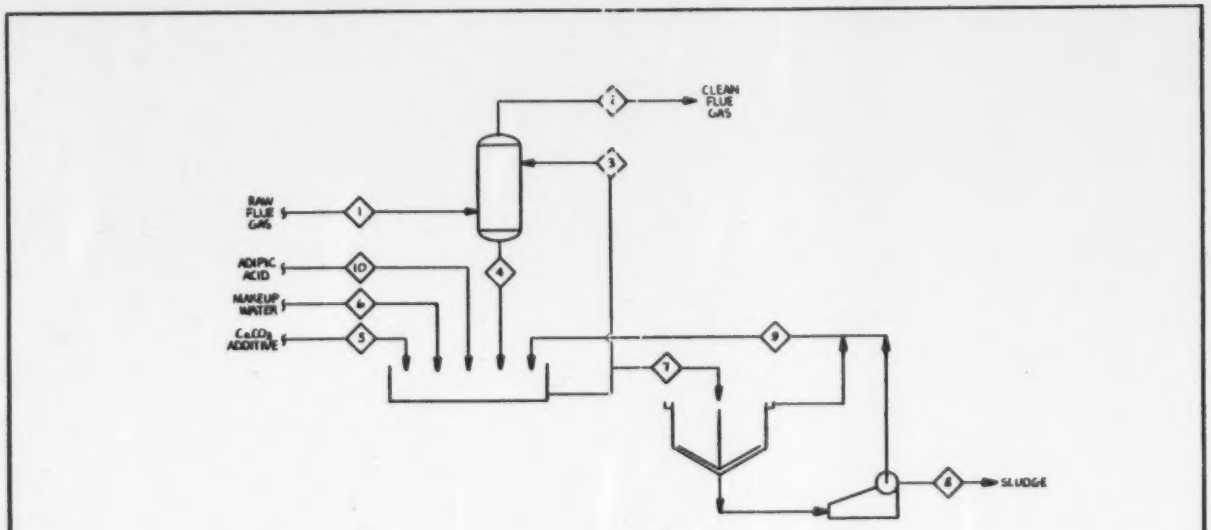


STREAM NUMBER / STREAM DESCRIPTION	1 INLET GAS	2 EXIT GAS	3 RECYCLE LIQUOR	4 SCRUBBER BOTTOMS	5 MAKEUP ALKALI	6 MAKEUP WATER	7 CLARIFIER FEED	8 SLUDGE	9 CLARIFIER RETURN	10 ADIPIC ACID
TOTAL FLOW RATE										
lbs./hr.	179,882	192,765	1.82×10^6	1.80×10^6	1250	14,993	17,974	3268	14,706	164
GPM			3240	3200		30.0	32.3	3.2	29.0	
TEMPERATURE (°F)	400	125								
GAS FLOW RATE										
lbs./hr.	179,882	192,765								
lb. MOLES/hr.	6202	6934								
ACFM	64,900	43,774								
SCFM	39,180	43,789								
LIQUID PHASE FLOW RATE										
lbs./hr.			1.64×10^6	1.62×10^6		14,993	16,177	1634	14,543	
SOLID PHASE FLOW RATE										
lbs./hr.			182,000	182,000	1250		1797	1634	163	164

ADIPIC ACID-ENHANCED LIMESTONE FGD PROCESS
BOILER SIZE: 150×10^6 BTU/hr.
COAL TYPE: EASTERN, 3.5% S
SO_2 REMOVAL: 90%

70C2203

Figure 4-1. Material balance for small boiler - limestone system (with adipic acid).

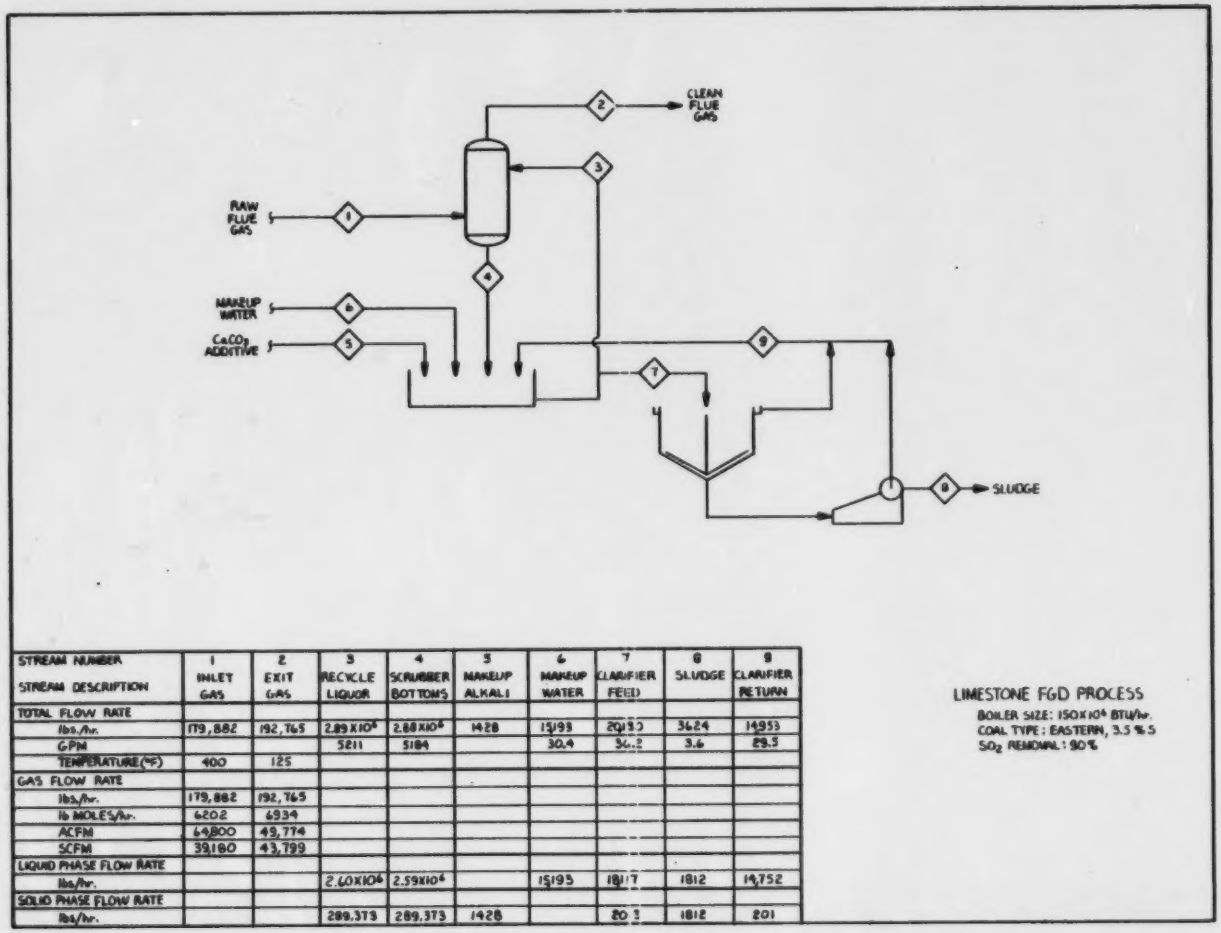


STREAM NUMBER / STREAM DESCRIPTION	1 INLET GAS	2 EXIT GAS	3 RECYCLE LIQUOR	4 SCRUBBER BOTTOMS	5 MAKEUP ALKALI	6 MAKEUP WATER	7 CLARIFIER FEED	8 SLUDGE	9 CLARIFIER RETURN	10 ADIPIC ACID
TOTAL FLOW RATE										
lbs./hr.	416,800	440,500	4.16×10^6	4.13×10^6	3328	30,430	46,322	6698	39,624	43.7
GPM			7480	7430		60.4	868	8.5	78.1	
TEMPERATURE (°F)	400	125								
GAS FLOW RATE										
lbs./hr.	416,800	440,500								
lb. MOLES/hr.	14,500	15,750								
ACFM	149,600	113,000								
SCFM	86,590	94,250								
LIQUID PHASE FLOW RATE										
lbs./hr.			3.75×10^6	3.72×10^6		30,430	43,430	4349	39,44	
SOLID PHASE FLOW RATE										
lbs./hr.			416,000	416,000	3328		4132	4349	483	43.7

ADIPIC ACID-ENHANCED LIMESTONE FGD PROCESS

BOILER SIZE: 400×10^6 BTU/hr.
COAL TYPE: EASTERN, 3.5% S
SO_2 REMOVAL: 90%

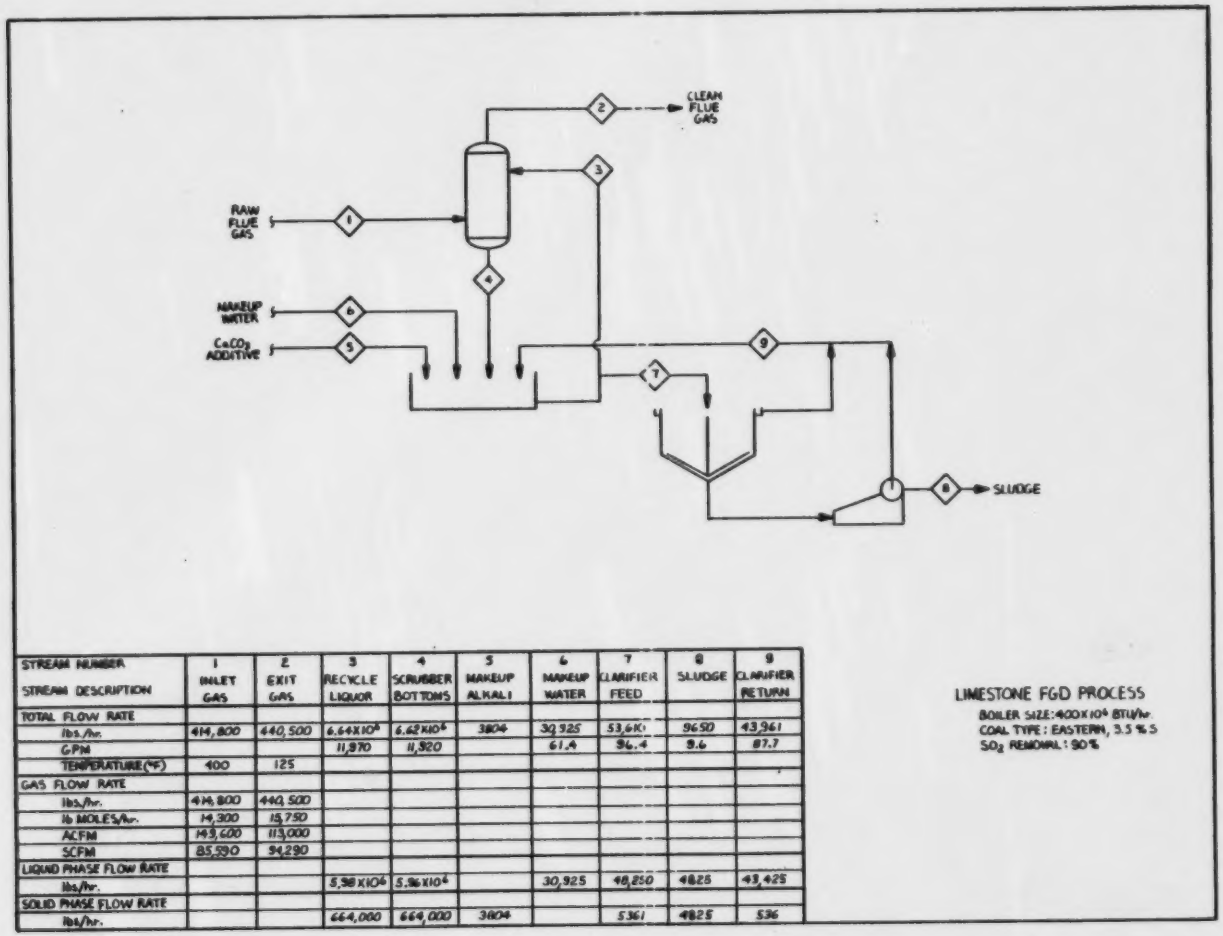
Figure 4-2. Material balance for large boiler - limestone system (with adipic acid).



STREAM NUMBER / STREAM DESCRIPTION	1 INLET GAS	2 EXIT GAS	3 RECYCLE LIQUOR	4 SCRUBBER BOTTOMS	5 MAKEUP ALKALI	6 MAKEUP WATER	7 CLARIFIER FEED	8 SLUDGE	9 CLARIFIER RETURN
TOTAL FLOW RATE									
lbs./hr.	179,882	192,765	2.89×10^6	2.68×10^6	1428	15193	20130	3624	14953
GPM			5211	5184		30.4	34.2	3.6	29.5
TEMPERATURE(°F)	400	125							
GAS FLOW RATE									
lbs./hr.	179,882	192,765							
lb MOLES/hr.	6202	6934							
ACFM	64,800	49,774							
SCFM	39,180	43,799							
LIQUID PHASE FLOW RATE									
lbs./hr.			2.60×10^6	2.59×10^6		15193	18117	1812	14752
SOLID PHASE FLOW RATE									
lbs/hr.			289,373	289,373	1428		2013	1812	201

LIMESTONE FGD PROCESS
BOILER SIZE: 150×10^6 BTU/hr.
COAL TYPE: EASTERN, 3.5 %S
SO_2 REMOVAL: 90%

Figure 4-3. Material balance for small boiler - limestone system (without adipic acid).



STREAM NUMBER / STREAM DESCRIPTION	1 INLET GAS	2 EXIT GAS	3 RECYCLE LIQUOR	4 SCRUBBER BOTTOMS	5 MAKEUP ALKALI	6 MAKEUP WATER	7 CLARIFIER FEED	8 SLUDGE	9 CLARIFIER RETURN
TOTAL FLOW RATE									
lbs./hr.	414,800	440,500	6.64×10^6	6.62×10^6	3804	32,925	53,6K	9650	43,961
GPM			11,970	11,920		61.4	96.4	9.6	87.7
TEMPERATURE(°F)	400	125							
GAS FLOW RATE									
lbs./hr.	414,800	440,500							
lb MOLES/hr.	14,300	15,750							
ACFM	143,600	113,000							
SCFM	85,590	94,290							
LIQUID PHASE FLOW RATE									
lbs./hr.			5.98×10^6	5.96×10^6		30,925	48,250	4825	43,425
SOLID PHASE FLOW RATE									
lbs/hr.			664,000	664,000	3804		5361	4825	536

LIMESTONE FGD PROCESS
BOILER SIZE: 400×10^6 BTU/hr
COAL TYPE: EASTERN, 3.5 % S
SO_2 REMOVAL: 90%

Figure 4-4. Material balance for large boiler - limestone system (without adipic acid).

although at RANGB, the makeup requirement was only slightly above the theoretical requirement. This difference in degradation rate could be due to the open loop operation of the RANGB. A sensitivity study of the cost effect of varying degradation rates is presented in Section 5.

In Section 4.2.1-4.2.4, the energy requirements for the following FGD unit process areas are presented:

- Raw Materials Handling and Preparation
- Liquid Pumping
- Fan
- Utilities and Services

4.2.1 Raw Materials Handling and Preparation

The majority of energy use in the raw material handling area is directly related to limestone consumption. This is lower for the adipic acid system due to better reagent utilization. The mass of adipic acid handled is about one hundredth the mass of limestone and therefore inconsequential as far as energy considerations are concerned. From the technology assessment report, the raw material handling energy requirement for the 150 million Btu/hour boiler was 9.5 KW_t (KW of thermal heat input) for the dual alkali system. Adjusting this by a factor of 1.05/1.2 (ratio of stoichiometries for the two systems), gives a value of 8.3 KW_t for the adipic acid-enhanced system. The energy requirement for the limestone system in the technology assessment report included limestone grinding power. In this study, a higher limestone cost was used to represent ground limestone. Consequently, the power requirements for the same size dual alkali system were used here.

4.2.2 Liquid Pumping

The first law of thermodynamics was used to calculate the liquid pumping requirements:

$$W_p n = \frac{P}{p} + \frac{g}{g_c} z + \frac{\bar{V}^2}{2g_c}$$

where:

W_p = pump work ($ft\text{-}lb_f/lb_m$)

n = efficiency (assume 0.6)

P = discharge pressure (lb_f/ft^2)

p = density (lb_m/ft^3)

g = gravitational acceleration (ft/sec^2)

g_c = conversion factor ($32.18\ ft\text{-}lb_m/lb_f\text{-}sec^2$)

z = pumping height (ft)

$\bar{V}$ = fluid velocity (ft/sec) (assume 10)

Using the design parameters discussed previously and the assumptions listed above, the following calculations are made:

$$W_p n\ (ft\text{-}lb_f/lb_m) = \frac{15\ (lb_f/in^2)(144\ in^2/ft^2)}{69.5\ lb_m/ft^3} + \frac{20\ ft\ (32.18\ ft/sec^2)}{32.18\ (ft\text{-}lb_m/lb_f\text{-}sec^2)} +$$

$$\frac{(10\ ft/sec)^2}{2(32.18\ ft\text{-}lb_m/lb_f\text{-}sec^2)}$$

$$W_p = 87.8\ ft\text{-}lb_f/lb_m$$

for the 150×10^6 Btu/hr FGD system.

The following equation was used to calculate the required horsepower:

$$PB(Hp) = \frac{\dot{m}Wp}{550}$$

where: PB = brake horsepower (Hp)

$\dot{m}$ = mass flow rate (lb_m/sec)

$\dot{m} = 1.82 \times 10^6$ lb/hr (1 hr/3600 sec)

$= 506\ lb_m/sec$

$PB = 506(lb_m/sec)(87.8\ ft\text{-}lb_f/lb_m)$

$(1\ Hp/550\ ft\text{-}lb_f/sec)$

$= 80.8\ Hp\left(\frac{1\ kW_e}{1.34\ Hp}\right)$

$= 60.3\ kW_e\left(\frac{1\ kW_t}{0.342\ kW_e}\right)$

$= 176.3\ kW_t$

4.2.3 Fan Energy Requirement

In order to calculate the fan energy requirement, a total FGD system pressure drop of 8 inches of water was used.

$$W_p n = \frac{\Delta P}{\rho}$$

$$W_p = \frac{1}{.6}\ \frac{(8\ in\ H_2O)(5.2\ \frac{lb_f/ft^2}{in\ H_2O})}{.08\ lb_m/ft^3}$$

$= 867\ ft\text{-}lb_f/lb_m$

$$PB = \frac{\dot{m}\ Wp}{550(1.34)}$$

$$\dot{m} = 179{,}882\ \frac{lb}{hr} \times \frac{1}{3600} = 50\ lb/sec$$

$PB = 58.5\ kWe = 172.1\ kW_t$

4.2.4 Utilities and Service

The utilities and service power requirement is based on the gas flow from the boiler which is the same for both FGD systems. Therefore, the value of 7.4 kW_t is used for both the base case and adipic-enhanced small boilers while the larger boilers use 17 kW_t.

4.3 COMPARISON OF ENERGY REQUIREMENTS

Table 4-2 summarizes the energy requirements for the base case and adipic acid-enhanced limestone systems. As a percentage of boiler heat input, the adipic process consumes approximately half as much energy as the base case limestone system.

TABLE 4-2. COMPARISON OF ENERGY REQUIREMENTS FOR INDUSTRIAL BOILER FGD SYSTEMS
(KW of thermal heat input)

Process Area	150×10^6 Btu/hr Capacity Boiler		400×10^6 Btu/hr Capacity Boiler	
	Adipic Acid System	Limestone System*	Adipic Acid System	Limestone System*
Raw Materials and Handling	8.3	9.5	22	25
Slurry Pumping	176.3	274.6	402.5	642
Fan Energy	172.1	408.7	396	842
Utilities and Service	7.4	7.4	17	17
TOTAL	364.1	700.2	837.5	1526
% of Boiler Heat Input	0.8	1.6	0.7	1.3

*Without adipic acid

SECTION 5

COST ANALYSIS OF ADIPIC ACID-ENHANCED LIMESTONE FGD SYSTEM

This section presents the results of an economic evaluation of an adipic acid-enhanced limestone FGD system. All of the costs are presented in mid-1978 dollars and are for FGD systems applied to new industrial boilers. The comparisons are between limestone FGD systems (with and without adipic acid) scrubbing the gas from 150 and 400 x 10^6 Btu per hour industrial boilers burning 3.5 percent sulfur Eastern coal. An SO_2 removal efficiency of 90 percent is required of both systems. It is expected that the cost trends found with this analysis will also hold for other sizes of industrial boilers. TVA has performed economic analyses on a utility-sized adipic acid-enhanced system which shows roughly the same trends.[21]

5.1 COST ELEMENTS AND BASES

The methodology and bases used for estimating capital investment and annual costs are presented in this section.

5.1.1 Capital Investment

Capital investments for the limestone FGD systems are estimated for four major areas: raw materials handling, SO_2 scrubbing, fans, and solids separation equipment. Design parameters were specified based on Shawnee prototype plant data and are summarized in Table 5-1. Vendor quotes were then obtained for the major equipment items in each area. Installation factors (using cost estimating manuals and/or vendor quotes) were used to estimate the total installed cost (direct capital costs).

TABLE 5-1. LIMESTONE FGD SYSTEM DESIGN PARAMETERS

Parameter	Without Adipic Acid	With Adipic Acid
Absorber Type	TCA	TCA
SO_2 Removal Efficiency (%)	90	90
Stoichiometry $\left(\frac{\text{moles sorbent}}{\text{mole } SO_2 \text{ removed}}\right)$	1.2	1.05
Gas Side Pressure Drop (total FGD system - inches H_2O)	17	8
TCA Bed Height (inches)	17	15
Slurry Pump Discharge Pressure (psig)	15	15
Pumping Height (ft)	20	20
L/G ($gal/10^3 acf$)	80	50

The raw material handling and preparation process area contains equipment such as storage silos, conveyors, screw feeders, mix tanks, agitators, and pumps. Because the limestone stoichiometry (Ca/S) is lower with adipic acid, the capital cost for the adipic acid case is lower than for the base case. An additional screw feeder and storage silo are included for addition of adipic acid. The raw material feed rates for each case were presented in Section 4.

The SO_2 scrubbing area (including the gas fan) is predominantly gas/liquid contacting and gas handling equipment. Accordingly, these costs vary with the L/G, gas flow, and ΔP requirements, and therefore are lower for the adipic acid case. Ductwork was not included in any of these cases, but the cost of the ductwork would be essentially the same for the limestone and adipic acid-enhanced systems.

The size of the solids separation process area varies with the amount of sludge being processed for each case. The better limestone utilization in the adipic acid case results in a smaller sludge volume which lowers this cost slightly. A thickener and vacuum filter are included in this process area for sludge concentration.

Indirect capital costs are those not attributable to the specific equipment items listed above and include:

- engineering costs,
- construction and field expenses,
- contractors' fee,
- allowance for funds used during construction,
- initial charge of chemicals and catalysts,
- start-up performance test,
- contingency costs, and
- working capital.

The indirect cost items were estimated as a percentage of the direct capital costs or of the annual direct operating costs. Specific percentages used in this study are indicated in Table 5-2.

TABLE 5-2. INDIRECT CAPITAL COST FACTORS[22]

Item	Amount
Engineering	10% of installed cost of 400×10^6 Btu/hr boiler for each case.
Construction and Field Expense	10% of installed cost.
Contractor Fee	10% of installed cost.
Start-up	2% of installed cost.
Performance Tests	1% of installed cost.
Contingency	20% of total direct and indirect costs.
Land	0.084% of total turnkey costs.
Working Capital	25% of total direct operating costs.

5.1.2 Annual Costs

The annual costs consist of three components:

- direct operating and maintenance costs,
- indirect operating costs, and
- annualized capital investment-related charges.

Direct operating and maintenance (O&M) costs include the following items:

- utilities,
- raw materials,
- operating labor,
- maintenance and repairs, and
- waste disposal.

Unit costs used to calculate the direct O&M costs are summarized in Table 5-3. The operating labor requirements were based upon one operator per shift and the supervision labor requirements were based upon 0.15 men/shift.[23] Maintenance costs were based upon estimates reported by TVA.[24]

TABLE 5-3. UNIT COSTS USED TO CALCULATE DIRECT O AND M COSTS[25] (1978 DOLLARS)

Item		Cost
Direct Labor	$/man-hour	12.02
Supervision	$/man-hour	15.63
Maintenance Labor	$/year	0.04 Total Direct Costs
Maintenance Material	$/year	0.04 Total Direct Costs
Electricity	$/kWh	0.0258
Process Water	$/m^3 ($/10^3 gal)	0.04 (0.15)
Limestone	$/kg ($/ton)	0.01984 (18.0)
Adipic Acid	$/kg ($/lb)	0.95 (0.43)
Solids Disposal*	$/kg ($/ton)	0.0166 (15.0)

*Reference 26

Utility and fuel requirements were calculated for each case using material and energy balances. Results of these calculations illustrate the variation in process energy requirements due to the use of adipic acid and serve as the basis for the energy costs reported in this section.

The second component of annualized costs is indirect operating costs. These costs include both payroll and plant overhead charges. In this study, payroll overhead was taken as 30 percent of the annual operating and supervision labor costs and plant overhead as 26 percent of the total annual labor and maintenance costs.[27] A 10 percent interest charge on the working capital was also assessed.

Annualized capital investment-related charges were calculated using the capital recovery method. The capital recovery factor was calculated from Equation 5-1:

$$CRF = \frac{i(1+i)^n}{(1+i)^n-1} \qquad (5\text{-}1)$$

where: i = interest rate
n = equipment life

In this study, the capital recovery factor was calculated assuming i = 10% and n = 15 years to be consistent with the FGD ITAR. The resulting capital recovery factor is 0.13.

G&A expenses of 4 percent were then added to produce an annual capital charge rate of 17 percent of the total capital investment.

5.2 CAPITAL INVESTMENT AND ANNUAL COST ESTIMATES

Tables 5-4 through 5-7 present the detailed capital and operating costs for the adipic acid-enhanced limestone FGD systems. Capital and operating costs for the base case limestone systems (without adipic acid) are listed in Tables 5-8 through 5-11. All areas of capital costs are lower for the

TABLE 5-4. CAPITAL INVESTMENT - LIMESTONE SYSTEM (WITH ADIPIC ACID) ON A SMALL BOILER

Boiler Capacity:	150 x 10^6 Btu/hr
Coal Feed Stock:	Eastern, 3.5% sulfur
SO_2 Control Level:	90%

Item	Cost (Thousands of 1978 dollars)
Direct Capital Costs	
Raw Material Handling	
Limestone	128
Adipic Acid	15
SO_2 Scrubbing	345
Fans	64
Solids Separations	208
Utilities and Services	46
Total Direct Costs (TDC)	806
Indirect Capital Costs	
Engineering[a]	156
Construction Expenses (0.1 TDC)	81
Construction Fees (0.1 TDC)	81
Start-up (0.02 (TDC)	16
Performance Test (0.01 TDC)	9
Total Indirect Cost (TIC)	343
Contingency (0.2 (TDC + TIC))	230
TOTAL TURNKEY COSTS (TTC)	1379
Land (0.00084 (TTC))	1
Working Capital (0.25 Direct Operating Costs[b])	108
TOTAL CAPITAL INVESTMENT (TCI)	1488

[a]Engineering cost = 0.1 TDC for 400 x 10^6 Btu/hr base case.

[b]From Table 5-5.

TABLE 5-5. ANNUAL COSTS - LIMESTONE SYSTEM (WITH ADIPIC ACID) ON A SMALL BOILER

Boiler Capacity:	150×10^6 Btu/hr
Coal Feed Stock:	Eastern, 3.5% sulfur
SO_2 Control Level:	90%
Operating Factor:	60%

Item	Cost (Thousands of 1978 dollars)
Direct Costs	
Operating Labor ($12.02/m-h)	105
Supervision ($15.63/m-h)	21
Maintenance Labor (0.04 TDC)	32
Maintenance Materials (0.04 TDC)	32
Electricity ($0.0258/kWh) (125 kWh)	17
Proc. Water ($0.04/$m^3$) (6.8 m^3/hr)	1
Solids Disposal ($0.0166/kg) (1482 kg/hr)	129
Limestone ($0.01984/kg)(567 kg/hr)	59
Adipic Acid ($0.95/kg) (7.5 kg/hr)	37
Total Direct Operating Cost	433
Overhead	
Payroll (0.3 x (1+2) above)	38
Plant (0.26 x (1+2+3+4) above)	49
Total	87
Capital Charges[a]	
Capital Recovery (0.17 TTC)	234
Interest on Working Capital (0.1)	11
TOTAL ANNUAL COSTS	765

[a]Capital charges include investment return of 10%; straight-line description, (15 yrs. FGD life) G&A, property taxes and insurance. Federal and State income taxes are not included.

TABLE 5-6. CAPITAL INVESTMENT - LIMESTONE SYSTEM (WITH ADIPIC ACID) ON A LARGE BOILER

Boiler Capacity: 400×10^6 Btu/hr
Coal Feed Stock: Eastern, 3.5% sulfur
SO_2 Control Level: 90%

Item	Cost (Thousands of 1978 dollars)
Direct Capital Costs	
Raw Material Handling	
Limestone	291
Adipic Acid	29
SO_2 Scrubbing	628
Fans	115
Solids Separations	328
Utilities and Services	83
Total Direct Costs (TDC)	1474
Indirect Capital Costs	
Engineering[a]	156
Construction Expenses (0.1 TDC)	147
Construction Fees (0.1 TDC)	147
Start-up (0.02 TDC)	29
Performance Test (0.01 TDC)	15
Total Indirect Cost (TIC)	494
Contingency (0.2 (TDC + TIC))	394
TOTAL TURNKEY COSTS (TTC)	2362
Land (0.00084 TTC)	2
Working Capital (0.25 Direct Operating Costs[b])	222
TOTAL CAPITAL INVESTMENT (TCI)	2586

[a]Engineering Cost = 0.1 TDC for 400×10^6 Btu/hr base case.

[b]From Table 5-7.

TABLE 5-7. ANNUAL COSTS - LIMESTONE SYSTEM (WITH ADIPIC ACID) ON A LARGE BOILER

Boiler Capacity:	400 x 10^6 Btu/hr
Coal Feed Stock:	Eastern, 3.5% sulfur
SO_2 Control Level:	90%
Operating Factor:	60%

Item	Cost (Thousands of 1978 dollars)
Direct Costs	
Operating Labor ($12.02/m-h)	105
Supervision ($15.63/m-h)	21
Maintenance Labor (0.04 TDC)	59
Maintenance Materials (0.04 TDC)	59
Electricity ($0.0258/kWh)(286 kWh)	39
Proc. Water ($0.04/$m^3$)(13.7 m^3/hr)	3
Solids Disposal ($0.0166/kg) (3945 kg/hr)	344
Limestone ($0.01984/kg)(1509 kg/hr)	158
Adipic Acid (0.95/kg)(19.9 kg/hr)	99
Total Direct Operating Cost	887
Overhead	
Payroll (0.3 x (1+2) above)	38
Plant (0.26 x (1+2+3+4) above)	63
Total	101
Capital Charges[a]	
Capital Recovery (0.17 TTC)	402
Interest on Working Capital (0.1)	22
TOTAL ANNUAL COSTS	1412

[a]Capital charges include investment return of 10%; straight-line description, (15 yrs. FGD life) G&A, property taxes and insurance. Federal and State income taxes are not included.

TABLE 5-8. CAPITAL INVESTMENT - LIMESTONE SYSTEM (WITHOUT ADIPIC ACID) ON A SMALL BOILER

Boiler Capacity:	150×10^6 Btu/hr
Coal Feed Stock:	Eastern, 3.5% sulfur
SO_2 Control Level:	90%

Item	Cost (Thousands of 1978 dollars)
Direct Capital Costs	
Raw Material Handling	
Limestone	147
Adipic Acid	-
SO_2 Scrubbing	368
Fans	69
Solids Separations	227
Utilities and Services	49
Total Direct Costs (TDC)	860
Indirect Capital Costs	
Engineering[a]	156
Construction Expenses (0.1 TDC)	86
Construction Fees (0.1 TDC)	86
Start-up (0.02 TDC)	17
Performance Test (0.01 TDC)	9
Total Indirect Cost (TIC)	354
Contingency (0.2 (TDC + TIC))	243
TOTAL TURNKEY COSTS (TTC)	1457
Land (0.00084 TTC)	1
Working Capital (0.25 Direct Operating Costs[b])	110
TOTAL CAPITAL INVESTMENT (TCI)	1568

[a] Engineering cost = 0.1 TDC for 400×10^6 Btu/hr base case.

[b] From Table 5-9.

TABLE 5-9. ANNUAL COSTS - LIMESTONE SYSTEM (WITHOUT ADIPIC ACID) ON A SMALL BOILER

Boiler Capacity:	150 x 10^6 Btu/hr
Coal Feed Stock:	Eastern, 3.5% sulfur
SO_2 Control Level:	90%
Operating Factor:	60%

Item	Cost (Thousands of 1978 dollars)
Direct Costs	
Operating Labor ($12.02/m-h)	105
Supervision ($15.63/m-h)	21
Maintenance Labor (0.04 TDC)	34
Maintenance Materials (0.04 TDC)	34
Electricity ($0.0258/kWh)(239 kWh)	32
Proc. Water ($0.04/$m^3$) (6.9 m^3/hr)	1
Solids Disposal ($0.0166/kg) (1644 kg/hr)	143
Limestone ($0.01984/kg) (647 kg/hr)	68
Adipic Acid ($0.95/kg)	-
Total Direct Operating Cost	438
Overhead	
Payroll (0.3 x (1+2) above)	38
Plant (0.26 x (1+2+3+4) above)	50
Total	77
Capital Charges[a]	
Capital Recovery (0.17 TTC)	248
Interest on Working Capital (0.1)	11
TOTAL ANNUAL COSTS	785

[a]Capital charges include investment return of 10%; straight-line description, (15 yrs. FGD life) G&A, property taxes and insurance. Federal and State income taxes are not included.

TABLE 5-10. CAPITAL INVESTMENT - LIMESTONE SYSTEM (WITHOUT ADIPIC ACID) ON A LARGE BOILER

Boiler Capacity:	400×10^6 Btu/hr
Coal Feed Stock:	Eastern, 3.5% sulfur
SO_2 Control Level:	90%

Item	Cost (Thousands of 1978 dollars
Direct Capital Costs	
Raw Material Handling	
Limestone	332
Adipic Acid	-
SO_2 Scrubbing	653
Fans	126
Solids Separations	361
Utilities and Services	88
Total Direct Costs (TDC)	1560
Indirect Capital Costs	
Engineering[a]	156
Construction Expenses (0.1 TDC)	156
Construction Fees (0.1 TDC)	156
Start-up (0.02 TDC)	31
Performance Test (0.01 TDC)	16
Total Indirect Cost (TIC)	515
Contingency (0.2 (TDC & TIC))	415
TOTAL TURNKEY COSTS (TTC)	2490
Land (0.00084 TTC)	2
Working Capital (0.25 Direct Operating Costs[b])	222
TOTAL CAPITAL INVESTMENT (TCI)	2714

[a]Engineering Cost = 0.1 TDC for 400×10^6 Btu/hr base case.

[b]From Table 5-11.

TABLE 5-11. ANNUAL COSTS - LIMESTONE SYSTEM (WITHOUT ADIPIC ACID) ON A LARGE BOILER

Boiler Capacity:	400 x 10^6 Btu/hr
Coal Feed Stock:	Eastern, 3.5% sulfur
SO_2 Control Level:	90%
Operating Factor:	60%

Item	Cost (Thousands of 1978 dollars)
Direct Costs	
Operating Labor ($12.02/m-h)	105
Supervision $15.63/m-h)	21
Maintenance Labor (0.04 TDC)	62
Maintenance Materials (0.04 TDC)	62
Electricity ($0.0258/kWh)(522 kWh)	71
Proc. Water ($0.04/$m^3$)(13.9 m^3/hr)	3
Solids Disposal ($0.0166/kg)(4377 kg/hr)	382
Limestone ($0.01987/kg)(1725 kg/hr)	180
Adipic Acid ($0.95/kg)	-
Total Direct Operating Cost	886
Overhead	
Payroll (0.3 x (1+2) above)	38
Plant (0.26 x (1+2+3+4) above)	65
Total	103
Capital Charges[a]	
Capital Recovery (0.17 TTC)	424
Interest on Working Capital (0.1)	22
TOTAL ANNUAL COSTS	1435

[a]Capital charges include investment return of 10%; straight-line description, (15 yrs. FGD life) G&A, property taxes and insurance. Federal and State income taxes are not included.

adipic acid cases because of lower process flowrates. Less limestone is used because of the better reagent utilization and this reduces both the raw material and sludge handling costs. The better SO_2 sorption capability which results in a lower slurry recirculation rate and a lower gas side pressure drop, reduces the SO_2 scrubbing and fan costs.

Comparison of direct operating and maintenance costs for the limestone system (with and without adipic acid) reveals a significant saving in electricity and solids disposal costs for the adipic acid-enhanced case. However, most of these savings are offset by the cost of the adipic acid. It should be noted that the adipic acid cost is based on a consumption rate five times higher than theoretically required by material balance considerations. This degradation rate is based on Shawnee results from high oxidation test runs.[28] At RANGB, the adipic acid consumption was only slightly higher than the theoretical rate, but the system operates in an open-loop fashion with no liquor returned from the pond. If the system were operated in a closed-loop mode, the adipic acid residence time would increase and the actual-to-theoretical ratio could rise substantially.

Since the adipic acid consumption could be different than that assumed, calculations were performed to measure the sensitivity of the annual cost to adipic acid degradation rate. If the adipic acid consumption rate were twice theoretical, the annual cost would be reduced by about $60,000 or four percent of the total projected annual cost for a 400 x 10^6 Btu/hr system. Likewise, if the consumption ratio were 8 instead of 5 times theoretical, the total annual cost would rise by about four percent. If the adipic acid consumption ratio is higher than 6.5 times theoretical, the cost advantage for the adipic acid-enhanced system compared to the limestone-only system is negated.

Table 5-12 summarizes the capital investment and annual costs of the two limestone systems and a dual alkali system on the two model boilers. The data show that the capital investment for adipic acid-enhanced systems is 5 to 6 percent lower than for the base limestone system and the reduction in annual costs is about 2 to 3 percent lower for the adipic acid system. As stated in the

technology assessment report, the dual alkali, lime, and limestone systems costs generally agree within 10 percent of each other.[29] Although the accuracy of the cost data presented here is about ±30 percent, the relative cost difference between the adipic acid-enhanced system and the base case limestone system is significant. The process configuration for each of these systems is identical, with differences only in equipment (and in adipic acid feed system in one case).

TABLE 5-12. COMPARISON OF FGD SYSTEM CAPITAL INVESTMENT AND ANNUAL COSTS FOR NEW INDUSTRIAL BOILERS (1978 DOLLARS)

Boiler Size (10^6 Btu/hr)	FGD System	Capital Investment ($1000)	Annual Cost ($1000)
150	Limestone	1568	785
150	Limestone with Adipic Acid	1488	765
150	Dual Alkali*	1657	778
400	Limestone	2714	1435
400	Limestone with Adipic Acid	2586	1412
400	Dual Alkali*	2576	1328

*Reference 30

Several pieces of equipment in the limestone base design were reduced in size to reflect process advantages for the adipic acid-enhanced system. Therefore, the capital investment difference is real even though the overall capital investment of the two systems is accurate to only ±30 percent. The difference in costs between the limestone and the dual alkali system, however, is not significant because of the large variation between the two process configurations.

SECTION 6

ENVIRONMENTAL IMPACTS OF ADIPIC ACID-ENHANCED LIMESTONE FGD SYSTEMS

The environmental impacts of the base case limestone FGD system have been thoroughly discussed previously.[31] Therefore, only the incremental effects of using adipic acid compared to the base case limestone system will be addressed in this section.

6.1 AIR POLLUTION

An FGD system is designed to reduce sulfur dioxide emissions to the atmosphere. For both the base case or adipic acid-enhanced limestone system, the design SO_2 removal efficiency is 90 percent. A 150×10^6 Btu/hr industrial boiler burning Eastern coal (3.5% sulfur), will emit 85 pounds per hour when the SO_2 removal is 90 percent.

Wet scrubbing systems also have the potential for particulate removal and/or generation. The EPA has investigated several mechanisms of removal and generation.[32] The use of adipic acid, however, should not change any of these conclusions. This is because particulate control involves physical rather than chemical mechanisms for removal. The adipic acid system will also have the water vapor plume characteristic of all wet scrubbing systems.

Some experimental studies have found low concentrations (<10 ppm) of light hydrocarbons in the exit gas from bench scale reactors using adipic acid. Propane and butane have been identified and are probably the result of the degradation of adipic acid. These levels are very small relative to the amount of CO and other partially oxidized compounds which are formed in the boiler.[33]

6.2 WATER POLLUTION

The adipic acid-enhanced system has a potential similar to the base case limestone system for water pollution. Both systems can be designed on a closed-loop basis so that the only water losses during normal operation occur with the sludge going to landfill. Inadvertent discharges may occur due to process upsets or heavy rainfall. At these times, the waste water would have a high dissolved inorganic solids concentration and would contain adipic acid. The adipic acid, being a hydrocarbon, would exert a small biological oxygen demand on the receiving body of water.

6.3 SOLID WASTES

Due to the lower limestone stoichiometry attainable with the adipic acid-enhanced system, the volume of sludge produced is smaller compared to the base case. For the 150 million Btu per hour system, this results in a reduction from 1800 to 1600 pounds per hour of solid waste. Additionally, although not specifically discussed in length in this report, TVA has observed at Shawnee, that forced oxidation of the scrubber solids when using adipic acid has several advantages over using adipic acid without force oxidizing the solids. These include producing gypsum, which dewaters and handles much better than the calcium sulfite/sulfate sludge produced in an un-oxidized system. However, in order to show the comparison of adipic acid on a relatively equal basis, this option was not examined in this report.

The long-term stability of un-oxidized adipic acid sludges compared to limestone sludges should not reveal any relative advantages or disadvantages for either sludge. The toxicity of both types of sludges has been studied. A Level 1 bioassay of Shawnee sludges with and without adipic acid shows no difference in toxicity or mutagenicity.[34]

Another study indicates that leachate from both adipic acid and non-adipic sludges have very low toxicity.[35] This study also shows that adipic acid does not impact the concentration of inorganic compounds in the leachate.

Although adipic acid is on EPA's hazardous materials list, this should not preclude its use as a FGD additive. This list sets maximum non-reportable amounts of compounds which could be discharged to rivers and lakes. The use of materials on the list is acceptable, provided efforts are made to prevent discharge greater than the "reportable quantity." Chemicals with a "D" material classification have a reportable quantity of 5000 pounds per discharge. Both adipic acid and lime are in category "D".[36] 5000 pounds is a major portion of an adipic acid inventory for an industrial boiler FGD system. The fact that adipic acid is one of many substances appearing on the hazardous materials list does not restrict its use in the nylon industry or even as a food additive.

6.4 OCCUPATIONAL EXPOSURE

Worker exposure to adipic acid is not a serious problem. As a food additive, it is not harmful in small quantities. Dust inhalation can be controlled by a filter mask if it becomes a problem. The most objectionable item associated with using adipic acid is an unpleasant musty odor. This is probably a result of adipic acid being degraded into valeric or butyric acids. This odor has been reported occasionally at Shawnee and Springfield, however, it does not appear to be a major problem, and it was not noticed in the testing at RANGB.

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